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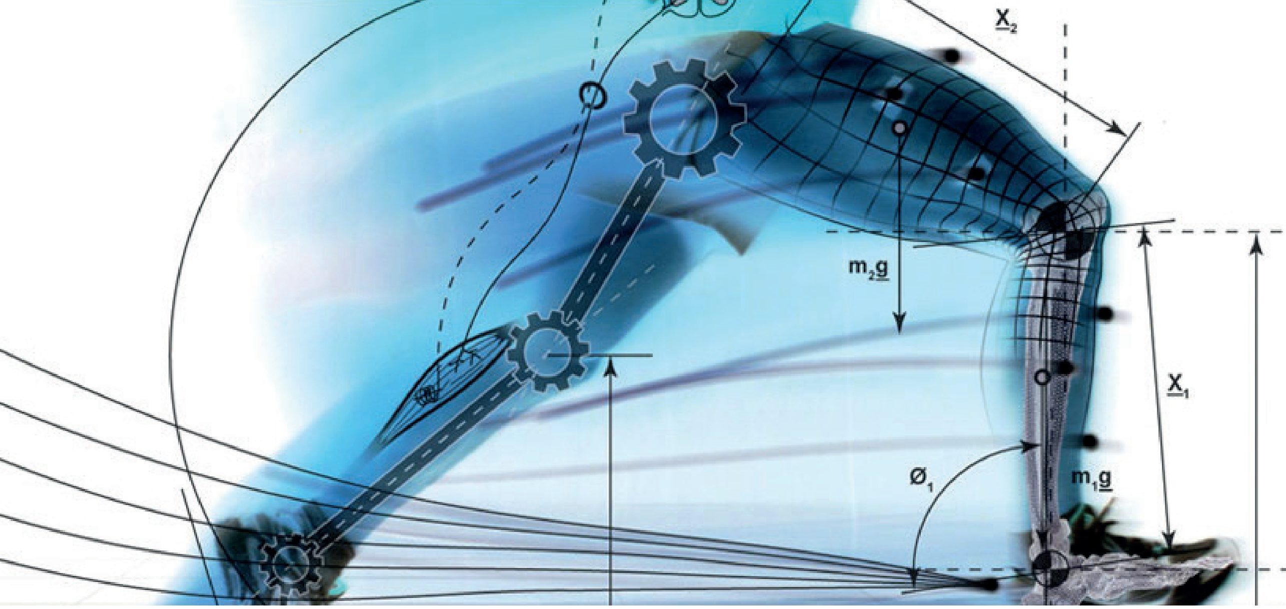

EFFECT OF FOOTWEAR ON MUSCULAR LOADING AND ENERGY DEMAND DURING DISTANCE RUNNING

BY
SHAHIN KETABI

DISSERTATION SUBMITTED 2016

AALBORG UNIVERSITY
DENMARK

EFFECT OF FOOTWEAR ON MUSCULAR LOADING AND ENERGY DEMAND DURING DISTANCE RUNNING

PH.D. THESIS

BY

SHAHIN KETABI

AALBORG UNIVERSITY
DENMARK

A DISSERTATION SUBMITTED TO
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PhD supervisor: Professor Uwe G. Kersting
Aalborg University

PhD committee: Associate Professor Jesper Franch (chairman)
Aalborg University

Professor, Dr., rer.soc. Stefan Grau
University of Gothenburg

Univ.-Professor, Dr. Wolfgang Potthast
German Sport University Cologne

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4. **Ketabi, S.**, Arendt-Nielsen, L. & Kersting, U. G. Footwear heel spring effects on ankle joint moment and Achilles tendon mechanics during running. *Submitted to Journal of Biomechanics*

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above.

CV

Shahin Ketabi was born in Kurdistan, Iran, in 1981. He received the B.Sc. and Master's Degree in physical education sport science as top student from Iran. He joined the Center of Sensory Motor Interaction, Health Science and Technology Department, Aalborg University, Aalborg, Denmark as Ph.D. follow under the supervision of Professor Uwe G. Kersting and Head of SMI Professor Lars Arendt-Nielsen. His academic research interests are sport biomechanics, injury biomechanics and clinical biomechanics. His Ph.D. research topic was on the effects of footwear interventions on ankle joint mechanics, Achilles tendon and muscle loading in relation to performance variables during distance running.

ENGLISH SUMMARY

The most popular activity around the world which involves the conversion of muscular forces into translocation through complex reciprocal movement patterns is running. Running economy is an important element of performance in distance running. A number of biomechanical parameters have been related to running economy and performance. Association of running mechanics with metabolic processes and economy is not well understood and very complex.

Footwear is typically a controlled variable with several design features which may influence economical running. Modifications to running shoes can be considered an obvious choice of modulating loading and with that running economy, performance and potentially overuse injuries. The muscular activations prior to touch-down are varied in response to changes in shoe construction, referred to as muscle tuning, possibly keeping the impact magnitude at an individually preferred level. The muscles around the knee and ankle joints may increase the joint stiffness, which appears to be related to better RE. Also the integration and timing of muscle activity to utilize the storage and release of elastic energy more effectively may lead to improvements in RE. It has been pointed out that substantially more elastic energy can be stored in in the muscle tendon unit of the triceps surae as compared to the energy return features found in footwear modifications.

This PhD thesis focuses on the effects of biomechanical parameters on running economy. Moreover, the effects of shoe inserts on calcaneal movement to affect energy stored in the ligaments and muscles of the foot and to modulate the energy storage and return mechanism of the triceps surae muscle group, muscle activity and running economy are investigated.

The results indicate that the energy consumption savings achieved by footwear most likely assist in improving RE by optimizing energy storage and return mechanisms within the biological system. Shoe-induced kinematic changes relate to overall metabolic cost where inserts can have the potential to regulate muscle activity and thus may affect running economy and muscle fatigue during prolonged runs. Footwear or insole interventions may alter gearing at the ankle joint and vertical force, and with that stretch in the Achilles tendon can be altered which potentially affects energy return within the musculoskeletal system. It is possible to relate gear ratio alterations to metabolic responses during a steady state treadmill run, however, the identified relationships are not direct as many factors need to be included.

DANSK RESUME

Den mest populære aktivitet rundt om i verden, der involverer omdannelse af muskuløse kræfter i frembevægelse gennem komplekse gensidige bevægelsesmønstre er løb. Løbeøkonomi er et vigtigt præstationselement i udholdenhedsløb. En række biomekaniske parametre har været relateret til løbeøkonomi og præstation. Forbindelsen mellem mekanik, metaboliske processer og økonomi er ikke godt forstået og meget kompleks.

Fodtøj er typisk en kontrolleret variabel med flere design features, som kan påvirke økonomien. Ændringer i løbesko kan betragtes som en oplagt måde for at modulere belastning og dermed økonomi, løbepræstation og potentielt overbelastningsskader. De muskulære aktiveringer inden touch-down varieres som svar på ændringer i skokonstruktion, også betegnet som muscle tuning, som muligvis holder belastningsstørrelser på et individuelt foretrukne niveau. Musklerne omkring knæet og ankelled kan øge ledstivhed, som synes at være relateret til en bedre RE. Den integration og timing af muskelaktivitet kan udnytte opbevaring og frigivelse af elastisk energi og kan føre til forbedringer i RE. Det er blevet påpeget, at væsentligt mere elastisk energi kan lagres ind i muscle tendon unit af triceps surae sammenlignet med energioptagelsesevner, der findes i fodtøj.

Denne Ph.D.-afhandling sætter fokus på konsekvenserne af biomekaniske parametre på løbeøkonomi. Desuden undersøges virkningerne af skoindlæg på calcaneus bevægelse som påvirker energioptagelse i ledbånd eller muskler i foden, og at modulere energioplagrings- og returmekanismer i triceps surae muskel gruppen, muskel aktivitet og løbeøkonomi.

Resultaterne viser, at energibesparelser ved fodtøj sandsynligvis bidrage til at forbedre RE ved at optimere energioplagrings- og returmekanismer i det biologiske system. Sko-induceret kinematiske ændringer vedrører samlede metaboliske ændringer, hvor indlæg kan have potentiale til at regulere muskelaktivitet og kan således påvirke løbeøkonomi og muskeltræthed ved længere løb. Fodtøj- eller indlægsinterventioner kan ændre gearing på ankelleddet og vertikalkraft, og med det stræk i akillessenen kan ændres som potentielt påvirker energi afkast indenfor bevægeapparatet. Det er muligt at relatere gear forholdsændringer til metaboliske reaktioner i løbet af en steady state løb dog de identificerede relationer er ikke direkte fordi så mange faktorer skal medtages.

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Shahin Ketabi

Aalborg, 2016

PUBLICATIONS AND RELATED WORK

The PhD thesis is based on the four papers and resulted from the four studies of the thesis:

PAPER 1

Improving running economy by biomechanical interventions - A systematic review of the literature. Shahin Ketabi, Lars Arendt-Nielsen, Uwe G. Kersting; Submitted to: Sports Biomechanics, 13-Jan-2015.

PAPER 2

The potential of insoles to alter pronation, muscle activity and running economy. Uwe G. Kersting, Shahin Ketabi, Lars Arendt-Nielsen; Submitted to: Journal of Sports Medicine, 26-Jan-2015.

PAPER 3

Effects of heel spring on lower limb muscular activity and running economy. Shahin Ketabi, Anderson Souza Oliveira, Lars Arendt-Nielsen, Uwe G. Kersting; Submitted to: Footwear Science 10/05/2015.

PAPER 4

Footwear heel spring effects on ankle joint moment and Achilles tendon mechanics during running. Shahin Ketabi, Lars Arendt-Nielsen, Uwe G. Kersting; Submitted to: Journal of Biomechanics, June 2015.

In addition the author has contributed to the following scientific work during the PhD:

- Modular Control of Treadmill Vs Overground Running. Anderson Souza Castelo Oliveira, Leonardo Gizzi, Shahin Ketabi, Dario Farina, Uwe G. Kersting. In Resubmission.

CONFERENCE ABSTRACT IN JOURNALS

- The Effects of Changes in Ankle Movement on, Muscle Activity, and Ground Reaction Forces during Running Acceleration; Shahin Ketabi, Uwe G. Kersting; *Barcelona –Spain; ECSS 2013*.
- Can Muscle Actions (Work) Calculated by a Musculoskeletal Model Explain Running Economy? Shahin Ketabi, Lars Arendt-Nielsen, Uwe G. Kersting; *Taipei-Taiwan; ISBS 2013*.
- Influence of Minimal Heel Inserts on Rearfoot Movement, Running economy, Mechanical Parameters and Muscular Activity During Distance Running; Shahin Ketabi, Uwe G. Kersting; *Natal, Brazil; Footwear Science*.

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LIST OF ABBREVIATIONS

COM:	Center Of Mass	QF:	Quadriceps Femoris
GPE:	Gravitational Potential Energy	RF:	Rectus Femoris
GRF	Ground Reaction Force	RMS:	Root mean Square
KE:	Kinetic Energy	SEE:	Series Elastic Element
OSF:	Optimal Stride Frequency	SOL:	Soleus
PSF:	Preferred Stride Frequency	TS:	Triceps Surae
RER:	Respiratory Exchange Ratio	VL:	Vastus Lateralis
RE:	Running Economy	VM:	Vastus Medialis
Ref:	Running Efficiency	$\dot{V}O_2$:	Rate of Oxygen Consumption
CE:	Contractile Element	RPE:	Ratings of Perceived Effort
EMG:	Electromyography	HR:	Heart Rate
GL:	Gastrocnemius Lateralis	TST:	Triceps Surae Tendon stiffness
GM:	Gastrocnemius Medialis	MTC:	Muscle-Tendon Complex
MTU:	Muscle–Tendon Unit	SD:	Standard deviation
MVC:	Maximal Voluntary Contraction	ANOVA:	Analysis of variance
PCSA:	Physiological Cross-Sectional Area		

CHAPTER 1. LITERATURE REVIEW

1.1. RUNNING ECONOMY

The previous 40 years have seen a substantial number of research publications on running shoes, their mechanical effects on the foot ankle and knee with a large focus put on the investigation of injury related parameters such as impact forces, stability as rearfoot pronation as the most named ones (Nigg 2001). More recent prospective studies have questioned the existence of unique relationships with injuries while rather limited studies were published on the possible effects of footwear on distance running performance. A good running performance should be characterized by maximizing energy efficiency. To achieve efficiency the metabolic system has to be well trained while the segmental movements have to be executed in a harmonic and well-coordinated way to keep energy consumption low (Bransford and Howley, 1976; Di Prampero et al., 1993).

Running Economy (RE) is typically defined as the metabolic energy demand for a given velocity of sub maximal running, and is determined by measuring the steady-state consumption of oxygen ($\dot{V}O_2$) and the respiratory exchange ratio (Saunders et al., 2004). Running is economical when the energy expenditure is small compared with the distance covered (Bransford and Howley, 1976; Costill et al., 1973). Running economy is measured as the steady–state oxygen cost per kilogram of body mass when running at given pace (Costill and Winrow, 1970; Mayhew, 1977), and more recently as the oxygen cost per kilogram of body mass per kilometer run (Bergh et al., 1991). Running economy can be quantified by the following formula:

$$\mathrm{RE} = \frac{\boldsymbol{VO2}\ \ (\boldsymbol{ml/min})}{\boldsymbol{Body\,Weight}\ (\boldsymbol{kg}) * \boldsymbol{Velocity}(\boldsymbol{Km/h})}$$

In studies of running, steady-state $\dot{V}O_2$at a single speed typically has been used as a measure of economy. Running economy can also be referred to as metabolic cost. Metabolic cost was shown to correlate very well with running performance (Costill et al., 1973; Conley and Krahenbuhl, 1979).

1.2. RUNNING EFFICIENCY (REF)

Several studies have shown a weak relationship between efficiency and economy of running (Saunders et al., 2004; Norman et al., 1976). The term “efficiency” is probably the most abused and misunderstood term in human movement energetic. Confusion and errors result from an improper definition of both the numerator and the denominator of the efficiency equation (Gaesser and Brooks, 1975; Whipp and Wasserman, 1969). There are two fundamental reasons for inefficiency:

inefficiency in conversion of metabolic energy to mechanical energy and neurological inefficiency in the control of that energy. Metabolic energy is converted to mechanical energy at the tendon, and the metabolic energy depends on the condition of each muscle, the metabolic state (fatigue) of muscle, the subject's diet, and any possible metabolic disorder. This conservation of energy is called metabolic or muscle efficiency and defined as follows:

$$\text{Metabolic (Muscle) Efficiency} = \sum \frac{\text{Mechanical Work Done by all Muscles}}{\textit{Metabolic Work of Muscles}}$$

$$\text{Mechanical Efficiency} = \sum \frac{\text{mechanical work (internal +external)}}{\text{metabolic cost} - \text{resting metabolic cost}}$$

The term "Economy" has emerged as the measurement which is both conceptually clear and practically useful for the evaluation of endurance activity and especially about running, and this term becomes almost universally accepted as the physiological criterion for "efficient" performance (Cavanagh and Kram, 1985). The current consensus is that running economy is an important element of performance in distance running in long and middle distance runners, and improvement in running economy could have a similar effect on performance as improvements in aerobic capacity.

1.3. MEASURMENT OF RUNNING ECONOMY

1.3.1. RUNNING ECONOMY MESURMENT; TREADMILL VS. OUTDOOR

To best characterize an efficient running technique the term running economy (RE) has been introduced and widely used. Running economy is typically assessed while running on a treadmill as running speed can be easily controlled and sufficiently precise respiratory exchange measurement cannot easily be transported with or by a runner during test situations merely due to their size and weight (Williams and Cavanagh, 1983). Further effects which might affect energy consumption such as wind resistance or changes in inclination or surface can be excluded providing a reliable test environment (Morgan et al., 1989a; Aura and Komi, 1986).

It has however been long debated if results from indoor treadmill measurement can be transferred to outdoor running, especially when running in competitions. Only very recently mobile oxygen consumption measuring devices have appeared on the market which seems to be able to assess RE under real-life running training conditions (Hausswirth et al., 1997; Worobets et al 2014). While these developments are promising their validation may be considered to be not yet sufficient. Any investigation aiming at identifying relatively small differences in oxygen consumption may therefore be best executed in the laboratory.

1.3.2. RUNNING ECONOMY RELIABILITY

Intra-individual reliability can be considered as being more important for intervention studies as subjects would serve as their own controls. When these repeated tests are spread over several days the variability of physiologic responses may mask the alteration achieved by the shoe modifications. Thus special as well as repeated tests in randomized order have been suggested as a solution. (Sunders et al., 2004, Astrand et al., 2007).

1.3.3. BODY MASS EFFECTED ON RUNNING ECONOMY MESURMENT

When investigating the effectiveness of interventions aimed at modifying RE the inter- and intra-individual variability of metabolic measurements have to been accounted for. In regard to inter-individual differences, the ratio of a runner's $\dot{V}O_2$ (l/min) should divided by his or her body mass (Tanner, 1964). However, for groups or individuals with different body mass this procedure may induce some problems because submaximal $\dot{V}O_2$ during running does not increase proportionately to body mass (Malina et al., 1971). Apart from the overall mass effect on RE, the pattern of distribution of mass within the body across the different segments is also affecting RE. In this respect carrying mass distally to the center of mass increases the aerobic demand of running to a greater extent than closer to the center of mass (Cavagna et al., 1991; Hogberg, 1952). This was shown by Jones et al. (1986), with an increase in $\dot{V}O_2$ of 4.5% per kilogram when additional load was carried on the feet. Further, a 7% per kilogram increase in $\dot{V}O_2$ was reported in that study when carrying mass on either the thighs.

Several other factors may affect inter-individual variation in RE, e.g., treadmill running experience, footwear, time of day when tested, prior training activity and nutritional status (Astrand et al., 2007).

1.4. FACTORS AFFECTING RUNNING ECONOMY

The following chapter provides a general literature review on factors affecting running economy. A more specific review covering the factors relevant for this doctoral thesis is found in paper 1 (Appendix), which lays the focus on the mechanical factors and RE (Figure 1).

1.4.1. TRAINING AND RE

It has been shown that training clearly could improve running economy and running performance. Also, several studies have shown that training would affect long distance running performance more than middle distance performance (Rowland, 1989; Ekblom et al., 1968). However, the relationships between factors that affect performance induced by mechanical or physiological mechanisms have not been clearly established (Costill et al., 1973; Daniels et al., 1978; Petray and Krahenbuhl, 1985).

Various forms of strength training have been shown to improve RE without increasing metabolic capacity which might be difficult for elite athletes who already train at the limit of their endurance trainability. It seems that these effects can be best explained by changes in the triceps surae MTU mechanical properties with a stiffer tendon in conjunction with stronger muscles can enhance energy storage and release mechanisms during ground contact. On the other hand, some authors believe that training related with improving performance and running economy could refine mechanical factors such as stride length and frequency, or integration and timing of muscle activity, and based on elastic energy that is stored and reused economy more economic running technique can be achieved (Costill et al., 1973; Brooks et al., 1996). A new paradigm from some studies about training is that a higher percentage of slow-twitch fibers in muscle are associated with better economy for running and performance, and economy may improve through reduced heart rate and ventilation subsequent to training (Bransford and Howley, 1976; Williams and Cavanagh, 1987; Bosco et al., 1987; Bailey and Pate, 1991).

1.4.2. ANTHROPOMETRY

The most variable factors which have been studied focused on anthropometric dimensions such as height, body mass, body size, limb size, and physique quantified by e.g., the ponderal index (the ratio of body weight divided by height). For instance some studies have characterized the elite long distance runners as Ectomorphic (women) or Ecto-Mesomorphic (men) with little body fat (Brown, 1971; Wells et al., 1981). Taylor and others have shown that, as a general rule of running energetics, the cost of running decreases with body size on a mass-specific basis. Also, there is clear evidence confirming that poor running economy of children and older adults compared with youngest adults are an age effect (Doblen, 1957; Astrand et al., 2007).

1.4.3. ENVIRONMENT

Environmental factors and parameters that affect performance are air density, wind speed and direction, training and competition surface. It has been shown that surface compliance; treadmill versus over-ground, air friction and resistance, and temperature and humidity has an effect on performance.

Oxygen uptake in track running has been measured in trained runners at sea level and altitude and the cost was significantly higher at sea level than at higher elevations (Bassett Jr et al., 1985). In regard to the surface or the running environment, some studies have shown that at higher speeds a greater difference in oxygen cost of over-ground versus treadmill running occurred (Bassett Jr et al., 1985; Morgan and Craib, 1992). The proportion of total energy cost absorbed by air friction is 2% for marathon and long distance running and 4% for middle distance running also 7.8% for sprinting (Davies, 1980).

1.5. PHSIOLOGY

1.5.1. GENDER

Oxygen cost of running at a given pace is smaller for men than for women (Bransford and Howley, 1976; Mayhew, 1977; Bergh et al., 1991; Cureton and Sparling, 1980). Bourdin et al. (1993) have shown that men demonstrated better economy than women because they are larger. Also some studies reported poor economy in women because of a higher percentage of fat, greater pelvic width and obliquity of the femur, and greater vertical displacement of the center of mass (Bransford and Howley, 1976; Cureton and Sparling, 1980; Sparling and Cureton, 1982).

1.5.2. AGE

Poor economy in young children and improvements with growth and maturity were mostly reported in cross-sectional studies (Astrand, 1952; Bourdin et al., 1993; Leger and Mercier, 1984; MacDougall et al., 1983; Rowland, 1989) as well as longitudinal data (Daniels et al., 1977; Daniels and Oldridge, 1971; Daniels, 1985; Krahenbuhl et al., 1989; Rowland and Green, 1988). There is evidence that running economy is better in younger adults compared with older adults (Daniels et al., 1978; Sidney and Shephard, 1977; Waters et al., 1983).

1.5.3. MUSCLE CONTRACTION

In regard to the literature, there are two muscle contraction related factors which influence energy cost and running economy. The first is the balance between concentric and eccentric contractions of individual muscles and the second is the velocity of contraction. It has been indicated that it is less costly for muscles to generate force at low muscle fiber contraction velocities. In fact, the generated force is highest and the metabolic rate is lowest during an isometric contraction while the energy cost for generating force for contraction increases with greater shortening velocity (Taylor, 1993). The balance between eccentric and concentric contractions could potentially influence running economy, because the eccentric contraction during which elastic energy is stored are less costly than the concentric contraction in which the energy is released (Williams, 1985).

1.6. BIOMECHANICS

Martin and Morgan examined the economy of movement are involved within four areas, i.e., body structure, kinematics, kinetics and biomechanical feedback or training (Martin and Morgan, 1992). The biomechanical parameters affected RE to a great extent which has been in the focus of this study and it was divided to two main branches, kinematic and kinetic parameters and Running Economy.

1.6.1. RUNNING ECONOMY & KINEMATIC PARAMETERS

Kinematics have a specific definition which would be the branch of mechanics that studies the motion of a body or a system of bodies without consideration of its mass or the forces acting on it, such as: distance and displacement, speed and velocity, acceleration (Hay, 1985).

Many studies on RE focused on kinematics within the legs and only a few studies have addressed upper body kinematics. Running technique has a large effect on running economy in terms of the amount of consumed oxygen changing the natural running technique. However, it is a difficult task to fully investigate mechanical contributions to RE by applying kinematic methods alone. Inter-individual variability in running economy has been explained by various physiological, biomechanical, environmental, anthropometrical and psychological factors. Biomechanical measures have identified that running economy is affected by the net vertical impulse of the ground reaction force, stride length, and change in speed during ground contact phase and vertical stiffness of a leg spring (Eriksson and Bresin, 2010).

It was hypothesized by Williams and Cavanagh that 54% of the inter-individual variations in RE can be explained by kinematic variables (Williams and Cavanagh, 1983; Williams and Cavanagh, 1987). Also, they reported that better economy in elite male distance runner was associated with greater maximal angle of thigh during hip extension and smaller knee angle at toe-off. Furthermore, Taylor has demonstrated that the time course of force development during locomotion, determines RE rather than the mechanical work that the muscles perform (Taylor, 1985). Other studies suggested that more obtuse knee angles should reduce the moments that the knee extensor have to exert since ground reaction force would have advantage shorter lever arm on the muscle (Alexander, 1991).

Furthermore, (Alexander, 1991; Hausswirth et al., 1997) showed that RE was impaired during the last 45 minutes of a marathon run on a treadmill, which was partly attributed to biomechanical factors such as a greater forward lean and a decrease in stride length. In respect to the relationship between the stride length and running economy is that the freely chosen stride length is most economical

(Cavanagh and Williams, 1981; Cavanagh and Kram, 1985; Cavanagh and Kram, 1989; Knuttgen, 1961) and evoked the greatest mechanical efficiency (Hogberg, 1952; Williams et al., 1987).

The biomechanical parameters examined (angular displacements between the ankle, knee and hip joints; joint angular velocities) did not very well predict RE (Chang and Kram, 1999). However, force production during ground contact; coupled with the activation of the leg extensors during the pre-activation and braking phases and their coordination with longer-lasting activation of the hamstring muscles were of importance (Keyrolinen et al., 2001). The authors pointed out that co-activation of the muscles around the knee and ankle joints increases the joint stiffness, which appears to be related to better RE. The action of the hip extensors also becomes beneficial in this respect during ground contact (Keyrolinen et al., 2001).

Refining mechanical elements such as stride length and frequency or the integration and timing of muscle activity to utilize the storage and release of elastic energy more effectively may lead to improvements in RE (Anderson and Tseh, 1994). Elastic energy stored during the eccentric contractions of running substantially contributes to propulsion via release during subsequent contractions (Aruin and Prilutskii, 1985; Cavagna and Kaneko, 1977). Inverse results also have shown that the relationship observed between biomechanical factors and running economy is weak and it has been concluded that descriptive kinematic and kinetic parameters alone cannot explain the complexity of running economy (Keyrolinen et al., 2001; Martin and Morgan, 1992).

Running involves the conversion of muscular forces to joint excursions generating complex movement patterns that utilize all the major muscles in the body. High performance running is reliant on skill and precise timing in which all movements have purpose and functions (Anderson, 1996). Clearly, changing aspects of running mechanics that result in a runner using less energy at any given speed is advantageous to performance (Cavanagh and Williams, 1981; Frederick, 1983).

Early research suggested that well trained runners running at 14 and 16 km/h were most economical at the runner's self-selected stride length, compared with other pre-determined stride lengths (Hogberg, 1952). More recent work has confirmed that the aerobic demand of running at a given speed is lowest at a self-selected stride length (Cavanagh and Williams, 1981; Farley and McMahon, 1992; Gullstrand et al., 2009).

More studies concluded that there is little need to dictate stride length for well-trained athletes since they display near optimal stride length (Cavanagh and Williams, 1981). The better RE in elite male distance runners was associated with a more extended lower leg at foot strike, a lower vertical force peak and a longer contact time (Williams and Cavanagh, 1987). More economical runners tend to exhibit less arm movement, as measured by wrist excursion during the stride (Anderson and Tseh, 1994; Cavanagh and Williams, 1981). Greater maximal plantar flexion velocity and greater horizontal heel velocity at foot con tact are also associated with better RE in elite male distance runners (Williams and Cavanagh, 1986).

Williams and Cavanagh studies also have shown a trend for more economical runners to exhibit less arm movement, as measured by wrist excursion during the stride. In this regard, other authors found that greater economy was associated with arm movement of lesser amplitude (Anderson and Tseh, 1994).It was shown that changes in stride frequency affected metabolic cost similarly during, uphill and downhill, running. In both uphill and downhill running, the asymmetrical energy fluctuations of the COM showed that the maximum possible elastic energy usage was reduced by 21% from level running (Snyder and Farley, 2011).

1.6.2. RUNNING ECONOMY & KINETIC PARAMETERS

The term kinetics entails the branch of mechanics that studies the actions of forces in producing or changing the motion of masses or kinetics is studying the motion of objects (particles/rigid bodies etc.) and the forces that cause those motions, such as: momentum, moment of force (torque), inertia, friction, gravity, mass, weight and force (Hay, 1985).

It seems that minimizing the external vertical and horizontal forces during running may enhance running economy. Reducing vertical forces might influence the stride length and frequency, whereas reductions in horizontal peak forces might be an object for a motor skill approach. Therefore, runners should minimize the vertical movement of the center of gravity and the horizontal braking in each running step to improve running economy and distance running performance (Storen et al., 2011). Some results have shown that arm movements tended to reduce total excursion of the body center of mass both laterally and horizontally (Williams and Cavanagh, 1986; Williams et al., 1987).

Others have found RE to be proportional to the weight supported, in that RE is directly dependent on the vertical forces (Farley and McMahon, 1992; Kram and Taylor, 1990). By increasing and decreasing horizontal resistance during treadmill running, horizontal forces contributed more than 33% of the total metabolic cost of horizontal running (Chang and Kram, 1999).

Many studies based on relationship between RE and biomechanical factors have been motivated by the suggestion that the differences of running economy between individuals might be explained from biomechanical factors (Cavanagh and Williams, 1981; Keyrolinen et al., 2001; Williams and Cavanagh, 1987). The intersegment couple components acting in the transverse plane during running had value within around ±20 N.m, and were due to synchronous activity of the upper limbs (Cappozzo, 1983). The intersegment couples in the frontal plan had peak-to-peak value in the range of 60 to 100 N.m, corresponding with control of lateral flexion by the contralateral erector spine.

1.6.3. EFFECT OF MUSCLE-TENDON STIFFNESS ON RUNNING ECONOMY

It was indicated that more efficient runners have different muscle-tendon complex stiffness, generally accepted that storage and reutilization of elastic energy in tendons substantially reduces energy demands in running (Cavagna and Kaneko, 1977). However, it is not known if and how economical runners could store and recover more tendon elastic energy compared with uneconomical runners. Hence, at this point, there is no conclusive mechanical explanation for the inter-individual differences in running economy (Di Prampero et al., 1986; Keyrolinen et al., 2001; Saunders et al., 2004; Williams and Cavanagh, 1987).

The amount of energy stored in a tendon depends on the mechanical properties of the tendon (compliance and rest length) and on the force that stretches the tendon. For a given kinematic pattern, and hence kinetic pattern, tendon force is inversely related to the moment arm of the tendon. The importance of moment arm scaling and locomotion energetics/elastic storage and return has been pointed out by others (Biewener, 2005; Carrier et al., 1994). At low level forces the more compliant quadriceps tendon and aponeurosis will increase the force potential of the muscle while running and therefore the volume of active muscle at a given force generation will decrease (Arampatzis et al., 2006).

Jared and Brian (2010) have demonstrated that both triceps surae tendon stiffness (TST K) and RE can change acutely, and that both variables appear to change together. It is speculated that this is a result of acute response to high-intensity training and/or a long-term training adaptation. The labile nature of the TST K and its resultant effects on cost of running suggests that this variable is an important one to consider in performances where EC is of importance (Fletcher et al., 2010). The main finding in this study was that there was a significant relationship between the relative change in average EC across all three measured running velocities and the relative change in TST K when all subjects were considered.

Furthermore, other results confirmed that a negative relationship exists between RE, measured as EC, and TST K, confirming the results of Arampatzis et al. (2006). This suggests that a higher TST K is associated with a lower energy cost to run a given distance. This observation must be tempered with previous suggestions that there appears to be optimal tendon stiffness, beyond which the energy cost of running must increase (Lichtwark and Wilson, 2007; Lichtwark and Wilson, 2008). It has been suggested that variables that describe muscle force production (i.e., force–length– velocity relationship and activation) are probably more suitable for explaining running economy (Martin and Morgan, 1992).

From a mechanical point of view there are two main issues that can affect the force–length–velocity relationship and the activation of the muscles while running. The mechanical advantages of the muscles (ratio of an agonist muscle group moment arm to that of the ground reaction force acting about a joint) may affect the force production in relation to the active muscle volume (Arampatzis et al., 2006).

1.6.4. FOOTWEAR INTERVENTIONS

Increased shoe weight will decrease running economy (Catlin and Dressendorfer, 1979; Jones et al., 1986) the added weight of orthotic-type inserts has also been shown to reduce economy during running (Burkett et al., 1985). Other studies have shown that the degree of cushioning of shoes has an influence on running economy; in this case well-cushioned shoes can reduce oxygen cost by as much as 2.8% over stiffer shoes of equal weight during running on a treadmill (Frederick et al., 1983; Frederick, 1983).

Modifications to running shoes can be considered an obvious choice of modulating loading and with that running performance and potentially overuse injuries (Nigg, 1986; Nigg and Wakeling, 2001). Some interventions have aimed at adding elastic components to footwear (Mercer et al., 2003; Morgan et al., 1989b) which may be impractical and only partly effective to improve energy return. The authors suggested that if the shoe provides inadequate shock absorption the runner produces great muscular effort to provide cushioning. Other studies reported that during running, footwear with midsole “Actuator Lugs” could improve running economy by 1% on trained distance runners (Moran and Greer, 2013).

While weight reductions of running shoes consistently show improvements in RE it cannot be concluded if minimalist shoes advance performance (Perl et al., 2012; TenBroek et al., 2013). Various footwear interventions appear to potentially improve RE but often with rather inconsistent effects, while some more recent footwear developments seem to show more generalizable effects. Therefore, in regard to these findings, the question arises how footwear alterations may affect the energy storage within the biological system as this will be the main and final question and goal of this thesis.

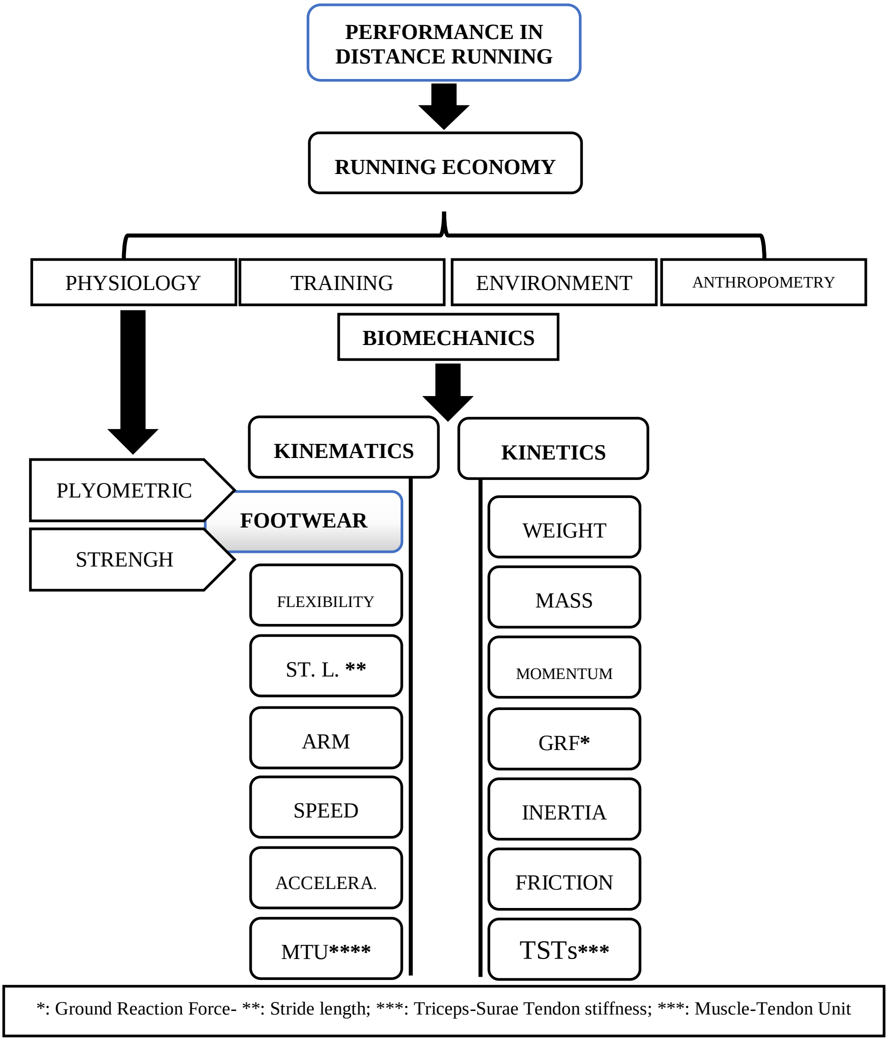

Figure 1: Factors affecting running economy. This schemetic provides and overview over the factors discussed in the literature review.

CHAPTER 2. AIM OF THE THESIS

It is known that RE is likely influenced by a number of factors; which include training experience, altitude, biomechanics and anthropometry, and also it is generally accepted that RE, which is a performance variable for distance runners, can be affected by parameters such as equipment, running technique, surface etc. Therefore, training interventions aimed at improving these factors may lead to improvements in RE and will conceivably lead to enhanced distance running performance. Regarding to the scope for footwear and training interventions to influence RE, the first general aim of the thesis was comparing between these two types of interventions through the literature to provide a conceptual foundation. Looking at selected footwear interventions served as the second aim based on the conclusion from the literature review that footwear changes can be provided which enhance RE based on energy return mechanisms within the shoe but also, and potentially more so, by a utilization of internal energy storage and release mechanisms within the musculoskeletal system. Therefore, the overall PhD project was designed to consist of four studies.

2.1. STUDY 1

The first objective of this PhD thesis was to identify the possible mechanisms behind the potential improvements in RE and to extract principles to guide researchers and coaches in how to make use of this potential. The first study was a literature review, using a search strategy yielding 28 intervention papers and four reviews which were suitable for inclusion. The main objective for the first paper was to focus on biomechanical parameters' effects on running economy. The posed question was if improving running economy by equipment or specific training interventions bears the greater potential. By this, a better understanding of interactions of biomechanical and physiological parameters can be provided which will enable coaches and practitioners to improve performance.

2.2. STUDY 2

The second objective of the thesis was to investigate the effect of moderate shoe inserts on calcaneal movement, muscle activity and oxygen consumption in running. There are two main factors which have always been linked to overuse injuries in running: impact force magnitude (or force rate) and rear-foot movement the amount of pronation (or velocity of pronation) during ground contact. However, no clear relationship, especially not in longitudinal studies on epidemiology and biomechanical factors, has ever been published. Therefore, the second paper (Experiment 1) was investigating the effect of moderate shoe inserts on calcaneal movement, muscle activity and running economy in distance running.

2.3. STUDY 3

It has been shown previously that substantial mechanical energy can be returned from the muscle-tendon unit of mainly the triceps surae which might allow for a potentiation of this effect by footwear. In Experiment 2 it was hypothesized that with decreasing heel spring a linear increase in RE would be observed. The purpose of third paper was to investigate the influence of three difference heel positions induced by insoles on lower limb muscular activity and $\dot{V}O_2$ and RE (performance variable) during steady state running.

2.4. STUDY 4

Despite attempting to keep body motion unchanged in a treadmill experiment it is possible that overall mechanics may change in regard to how the foot and ankle are loaded. Therefore, the purpose of the final study (Experiment 3) was to assess how heel height affects ground reaction forces, ankle joint mechanics and Achilles tendon gear ratio by providing a full three-dimensional analysis of the same intervention. It was hypothesized that insoles would allow for altering the gearing at the ankle, by this change the stretch in the Achilles tendon having an effect on indirect measures of running economy, namely perceived exertion and heart rate.

CHAPTER 3. METHODOLOGICAL CONSIDERATIONS

3.1. SUBJECTS

Healthy experienced runners were recruited for this project. Testing sessions were maximum 2.5 h in time. Most of the time was used for subject preparation with only limited time periods for the actual testing. For each part of the study, subjects were initially recruited and informed about the details of the experiments. A consent form was provided and if the subjects agreed to the study, they were asked to sign the consent form. The ethical approval was obtained from N-20130015 by The Research Ethics Committee for North Denmark Region and Ref. 2002/002 The University of Auckland.

3.2. ELECTROMYOGRAPHY (EMG)

Single use surface electrodes AMBU (AmbuNeuroline 720 01-K/12; Ambu, Ballerup, Denmark) were used to measure the electrical activity from the desired muscles. The skin was shaved and cleaned and the electrodes are placed according to recommendations from Cram et al. (1998) and SENIAM (2005). Electromyography electrodes bipolar recording were placed on muscles of interest after standardized skin preparation.

Up to nine muscles of the lower and upper limb were evaluated with standard EMG for assess muscle work and intensity; see SENIAM guidelines for surface electromyography. These muscles were: the tibialis anterior (TA), the soleus (SO), the gastrocnemius medialis (GM) and lateralis (GL), the peroneus longus (PL), the biceps femoris (BF), the vastus medialis (VM) and lateralis (VL) of the quadriceps, the rectus femoris (RF) Gluteus Maximus (GL).

EMG data were band pass filtered at 20 – 500 Hz with a zero phase-lag 4th order Butterworth filter, fully rectified and, subsequently, low pass filtered at 10 Hz. The resulting envelopes were integrated (iEMG) over the whole stride (CYC) (touch-down until subsequent touch-down) and over a period of 50 ms prior to pre-TD. For each muscle of each subject, the maximum EMG amplitude from one step cycle of the Normal condition was used to normalize EMG amplitudes (based on running methodology at least 8 steps were needed and necessary to analyze). Subsequently, integrated EMG (iEMG) and pre-activation (EMGPRE) were calculated for each muscle separately for the three conditions and averaged over the number of collected steps per condition. All signal processing was performed in Matlab (Vers. 7.3, The Math Works, USA).

Subjects had to carry a small bag on their back which holds the amplification and storage unit for electromyography signals (Figure 2).

Figure 2: Backpack including minicomputer (UMPC-ViliV) and Stand-Alone Wireless Sync-Trigger system (Noraxon), 1380 g total weight with dimensions indicated in the picture.

(Moritani and Yoshitake, 1998) have shown that the EMG analyses integrated over several cycles of a repetitive movement will linearly relate to oxygen consumption ($\dot{V}O_2$). Therefore, if muscle activity during running would be varied due to changes in footwear or foot movement either during pre-TD or over the whole running cycle a corresponding change in oxygen consumption should occur (Reinschmidt et al., 1997). The relative EMG activities for the whole step cycle (CYC) were multiplied by the relative muscle physiological cross-sectional area taken from cadaver data (Horsman et al., 2007) and summed up over the muscles tested to estimate variations in total neuromuscular effort (TNME) based on Moritani and Yoshitake.

3.3. RUNNING ECONOMY AND $\dot{V}O_2$

For each participant, running economy was determined as the rate of oxygen consumption ($\dot{V}O_2$) per kg body mass when running at the individual's preferred speed or at 80% of their 5000 m best, and based on the participant's background as they were experienced long distance runners. The tests were submaximal running tests. Oxygen consumption ($\dot{V}O_2$ in ml.kg^{-1}.min^{-1}) was measured during a 12-16 min period using a breath-by-breath spirometer. The spirometer was calibrated before each session by means of a two-point calibration using environment air and a gas mixture.

The last two minutes of steady-state of running which was collected by two different gas analyzers the first one from New-Zealand (MOXUS Metabolic measurement system, AEI Technologies, Inc., USA) and other one in Denmark (CareFusion version 02- USA) were averaged as oxygen consumption for each condition (Alexander, 1991; Aruin and Prilutskii, 1985; Brooks et al., 1996). Oxygen uptake was calculated from measures of ventilation and the oxygen and carbon dioxide in the expired air.

At the conclusion of each test run, subjects were asked to rate the perceived exertion (RPE) of the shoe condition on a 10-cm visual analog scale. Further methods of estimating effects of interventions on RE are the Rating of Perceived Exertion (RPE) which relates perceptions of effort to physiologically measurable as heart rate, respiration intensity, breathing rate, sweating or fatigue. Perceived exertion is how hard you feel like your body is working. Although this is a subjective measure, a person's exertion rating may provide a reasonable and reliable estimate of the actual metabolic load during physical activity (Borg, 1998). It is not clear if such measures would allow for a differentiation of intervention effects but as these are commonly used they may bear the potential for additional information. 1= very comfortable and fine, 10= worst imaginable discomfort (Foster, 1998). It has been demonstrated to be a valid measure of both aerobic and anaerobic exercise (Foster et al., 2001; Gabbett, 2003).

3.4. TWO-DIMENSIONAL MOVEMENT ANALYSIS (2D)

Sagittal plane kinematics and static and dynamic angle position between segments (shank, foot) were obtained by a 350 Hz video camera in Denmark (Basler scout, Winterthur, CH) and by a 100 Hz camera (A103f, Basler Switzerland) in New Zealand. The camera was mounted 2 meter away next to the treadmill at a height of 0.2 m above treadmill surface level. Five retro-reflective markers were placed on the metatarsus number 5, lateral calcaneus; lateral malleolus; lateral femoral condyle and greater trochanter of left leg. An imaginary line between lateral calcaneus to lateral malleolus was considered as A and imaginary line between lateral malleolus to lateral femoral condyle was considered as a B so that, angle between lines A and B was determined as the ankle angle. Similarly, the foot segment angle, the knee angle and the thigh angle in respect to the vertical were defined. Specific holes were embedded on the shoes to assess the alteration of foot displacement induced by insoles into shoes (Figure 3).

Figure 3: Left shoe with large enough holes for 5th metatarsal and calcaneus displacement monitoring (study 3 and study 4).

3.5. THREE-DIMENSIONAL MOVEMENT ANALYSIS (3D)

Retro-reflective markers were affixed to the skin over anatomical landmarks and secured with medical tape. In total, 55 retro reflective markers were positioned on bony landmarks on the body. An eight-camera Qualisys high-speed video system (Oqus 300 series, Qualisys, Sweden) was used for kinematic data collection. The 3D motion capture data were analyzed in visual 3D. According to standard procedures, Segments and joints were defined based on reference and tracking markers (Figure 4).

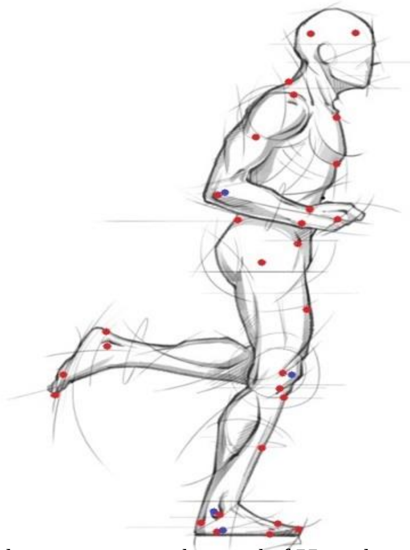

Figure 4: Full-body marker set-up protocol; a total of 55 markers was used, figure is showing one side of the body.

For data representation, the first and last 5% of the stance phase were excluded because of the low GRF and the consequently unreliable calculation of the point of force application (Phase1: 5–20%; Phase2: 20–40%; Phase3: 40–60%; Phase4: 60–80%; Phase5: 80–95%). The joint angles were described by the orientation of the distal to the proximal segment coordinate system (Braunstein et al., 2010). The ankle gear ratio (GRankle) was calculated as the ratios of the moment arms of the ground reaction force (R) acting on ankle joint to the agonist’s tendon moment arms (r) (Carrier et al., 1998). The gear ratio, defined as the ratio of the moment arm of the ground reaction force (GRF) to the moment arm of the counteracting muscle tendon unit, is considered to be an indicator of joint loading and mechanical efficiency (Braunstein et al., 2010; Maganaris et al., 1998; Herzog and Read, 1993).

3.6. FORCE PLATES AND TIMING GATES

Cameras also were synchronized with three force plates on the ground (AMTI, OR6/7 1000, Watertown, MA, USA). The same speed as used during warm-up on the treadmill was selected for each trial and it was controlled by timing gates (Newtest Powertimer 300 series, Newtest Powertimers, Finland). Inverse dynamics was applied to calculate ankle joint moments in Visual3D (c-motion) (Figure 6). The calculation of gear ratios was executed in Visual3D based on the procedures documented by Carrier et al. (1994). All parameters were determined according to Braunstein et al. (2010) for the 5 phases of contact (Phase1: 5–20%; Phase2: 20–40%; Phase3: 40–60%; Phase4: 60–80%; Phase5: 80–95%).

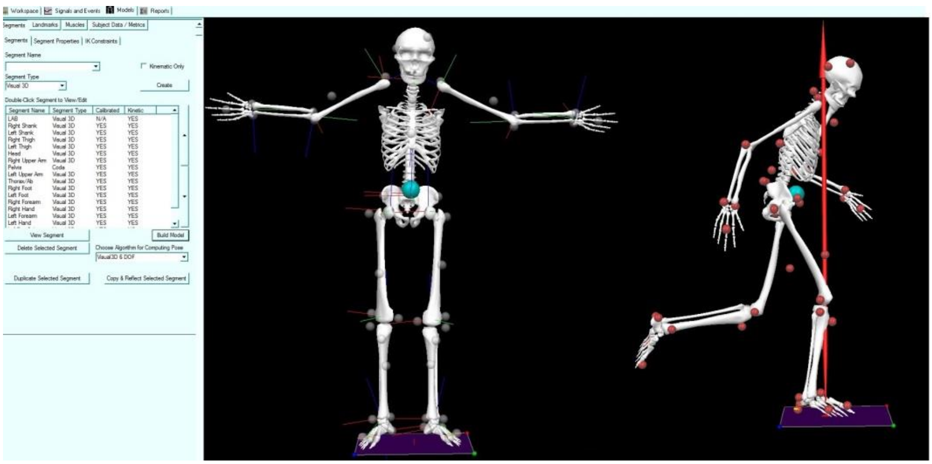

Figure 5:Visual3D (c-motion) static and running kinematic analysis.

3.7. TESTING PROCEDURES

Exercise was performed on an appropriate ergometer treadmill (Woodway Pro, Foster Court Waukesha, USA). Subjects had run on standard treadmill in the different experimental protocols but no longer than 50 min (including warm-up). Subjects had to carry a small bag on their back which holds the amplification and storage unit for electromyography signals during running. Subjects were asked to wear a custom designed pair of tights to cover and secure cables, electrodes and markers. Also they were asked to wear shoes provided by the principal investigator to control for this factor.

For study 2 difference Specific minimal insoles prepared (Figure 7). Based on the goal for study 3, retro-reflective markers were affixed on the shoes during running (Figure 7). Three differences insole prepared for study 3 and 4 to have ankle displacement (Figure 8). One or two short static reference trials were needed to be recorded while the subjects stand quietly on the force platform or treadmill.

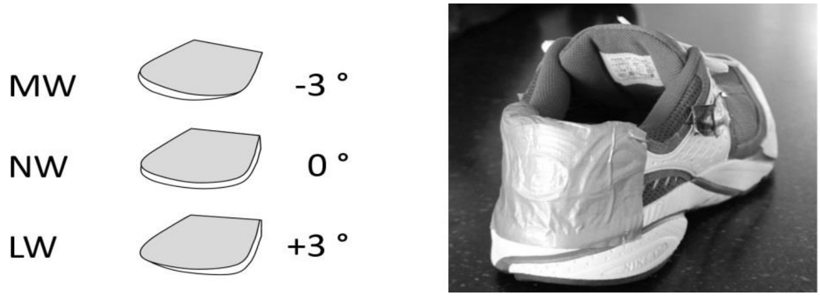

Figure 6: Different minimal insoles under the heel. Running shoe with modification to accommodate the in-shoe goniometer (study 2).

Figure 7: Five retroreflective markers were affixed to the right shoe: toe, 1st and 5th metatarsal, medial and lateral calcaneus (study 4).

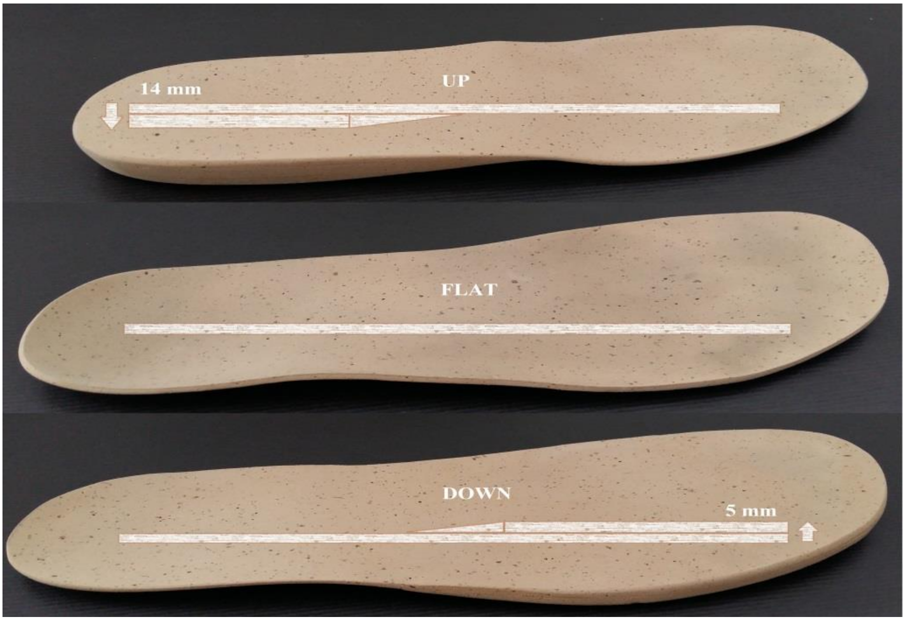

Figure 8: Up, Down and Flat insole used for ankle displacement (study 3 and study 4).

CHAPTER 4. DISCUSSION

The first goal of this PhD project was to investigate the potential of specific non-cardiovascular-targeted training interventions and footwear modifications on running economy in trained runners the second goal was to focus on the potential of footwear interventions and to investigate the mechanical effects of such interventions to explain the alteration in running economy.

The first study was a review paper which investigated ‘non-endurance’ training programs or footwear interventions to improve running economy in runners. Training interventions show consistently positive effects if the intervention entails a strength component with eccentric or heavy strength training regimens being most efficient while stretching, in most cases, does not acutely improve RE or may even be counterproductive. Based on the papers reviewed the main muscle group leading to these changes may be the plantar flexors of the foot. In regard to footwear interventions a great potential was demonstrated with the results across the different studies being more inconsistent as for the training interventions. This may lay in large parts in the considerable variety of different alterations used in these studies. For example, some studies were reviewed where only movement control (rearfoot movement) design parameters were altered while others compared standard shoes to minimal footwear (Rubin et al., 2009; Perl et al., 2012; Worobets et al., 2014). Thus it is not surprising that in the latter experiment substantial changes in running technique were found which make it difficult to isolate mechanisms. From this review it was concluded that both ‘non-endurance’ training as well as footwear interventions have the potential to improve RE without affecting metabolic capacity. It was suggested and discussed that both interventions likely rely on a change in energy storage and release within the musculoskeletal system.

It appears that midsole hardness or elasticity is a factor which has been repeatedly investigated, however, with inconsistent results indicating that it may not be the elasticity of the material itself which allows for energy storage and release alone. This interpretation is strongly supported by a paper comparing soft and viscous midsole materials (Nigg et al., 2003). In this study there was no group effect but the authors suggested that different individuals adapt a different muscle recruitment strategy. They did however merely track shoe movement which does not allow to describe the possible effects of midsole alterations onto the movement of foot segments, which was a major methodological component in the experiments of this PhD project. In the review paper it was indicated that individuals may adapt differently to changes in footwear based on their anatomical or metabolic characteristics. Therefore, the three experiments in this PhD project were designed around footwear interventions which were comparably small but aimed at isolating or reducing the possibly involved mechanisms.

In Experiment 1 it was investigated how moderately wedged inserts (+/-3°) affect frontal plane kinematics, muscle activity in the lower extremity and metabolic energy requirements during steady state running. In Experiment 2 it was assessed how insoles with different heel spring affect sagittal plane ankle kinematics during ground contact and how this relates to RE. In both studies, it was aimed at relating the induced kinematic changes to muscular activity in the lower extremity and metabolic energy requirements during steady state running on a treadmill. The aim of the final experiment (Experiment 3) was to investigate how different Achilles tendon stretch by inserts altering the heel spring within a running shoe during ground contact would alter the gearing at the ankle, and how such an alteration would affect indirect measures of running economy, namely perceived exertion and heart rate.

The results of Experiment 1 were comparable to Nigg et al. (2003) with no statistically significant differences between inserts across the whole group while individuals varied up to +/-5% in oxygen consumption. It was attempted to relate the iEMG changes to the physiologic parameter $\dot{V}O_2$ by summing the relative differences for each tested muscle group multiplied by the fraction of the relative volume of these eight muscles (Klein Horsman et al., 2007a) to a factor termed total neuromuscular effort (TNME) according to (Moritani and Yoshitake, 1998). With only eight muscles included this estimation comes with the limitation that all muscles would need to be included. This will be impossible in an experimental study as not all muscles of the locomotor system can be accessed by surface EMG. It was, however, not unlikely that including the main lower extremity muscles would show some relationship.

It was confirmed that shoe insoles affected the maximum ankle angle and range of motion during the first half of stance which potentially allows for altered energy storage and release in the elastic components of the foot ligaments and small muscles (Alexander et al., 1987) but also, and maybe more importantly in the muscles of the shank including the triceps surae. However, there were no systematic variations of RE while individual subjects showed considerable differences between insoles. For the EMG a reduced plantar flexor activity was shown for the lateral insole, while some alterations for muscles crossing the knee joint were observed. It is therefore possible that the small changes by the chosen insoles were not drastic enough to affect energy consumption. Alternatively, it may well be that changes of muscles around the knee joint are modulating the effects at the ankle joint.

The second experiment aimed at altering the sagittal plane ankle kinematics by inserts. The material of the insert aimed at minimizing potential energy return by the shoe in order to isolate the effect of altering ankle joint kinematics and with that triceps surae mechanics. This intervention was successful in the standing condition and the maximum ankle dorsiflexion during stance being systematically altered. While there was only a significant difference between the down and up condition there were also changes in ankle angle and foot orientation at TD which make the range of ankle movement during stance significantly different and systematic between all insole conditions of this study. As knee kinematics and stride rate remained similar between conditions it can be excluded that any other major change in strike pattern or running style occurred and that the main effect of the footwear intention was the intended alteration of triceps surae stretch. Following this line of thought, the Down condition was confirmed to require the least amount of contraction of the thigh and leg muscles while the stretch of the gastrocnemius MTU was greatest. However, these effects did not alter metabolic cost of running significantly. A possible explanation may be that a stretch of a complete MTU does not exclusively affect the series elastic element.

The final experiment (Experiment 3) results showed that the same insole interventions altered gearing at the ankle joint, the vertical force, and the stretch in the Achilles tendon. This alteration would be more likely to affect the energy exchange in the triceps surae. Therefore, this alteration could have an effect on indirect measures of running economy. It can be stated that the first hypothesis on insoles allowing to alter the gearing at the ankle was confirmed.

Differences in the heel position induced by insoles during static and dynamic conditions were mainly affecting the length of the moment arm of the GRF and were a reason of the differences in gear ratio and resultant joint moments. From a mechanical point of view the moment arm of the GRF depends on the direction of the GRF vector and the Position Force Application (PFA) with respect to the joint axis of rotation. It was observed that insoles were perceived as different between interventions with the Flat condition being significantly less exerting than Down. However, such perceptions can be influenced by both, the perception of shoe mechanics and comfort as well as a true effect on cardiovascular responses. It has to be noted that Heart Rate showed no significant differences between insoles. As mentioned by other researchers and in the discussion above, there were individual differences in the extent of ankle angle change in response to the inserts. In fact, screening across all individuals showed that some individuals responded according to the insert while others showed only marginal differences.

As Experiments 2 and 3 were conducted in close succession of each other there were 11 subjects for which results from both are available. This allows to investigate the relationship between the maximum difference in triceps surae stretch, i.e., the value for the insert with the largest stretch minus the value for the shoe with the smallest stretch, and the respective difference in steady state oxygen consumption measured on the treadmill (Figure 3). This correlation is negative ($p=0.09$), indicating a decreased energy consumption with increasing change in Achilles tendon stretch which would theoretically allow for a greater energy storage and return during ground contact. While this observation represents only a trend it indicates a possible basis for future research on the individuality of footwear adaptations.

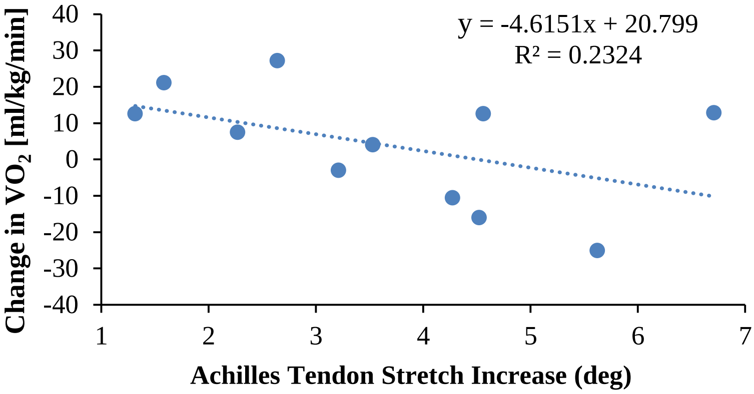

Figure 9: Correlation over 11 subjects. Correlation of maximum Achilles tendon stretch with the change in $\dot{V}O_2$ *consumption between the respective insole types.*

Overall, it is likely that not just one single mechanism can be identified which generates the potential benefit for all individuals. A combination of results from the last two studies may allow for providing a link between gear ratio and economy as it was postulated in previous studies.

This PhD project has confirmed that inserts allow for a systematic alteration of foot movement during running within a running shoe while the induced alterations in muscular or physiological responses are related but are quite individual and cannot be directly linked to RE.

CHAPTER 5. FUTURE DIRECTIONS AND PERSPECTIVES

Based on the review paper, various forms of strength training have been shown to improve RE without increasing metabolic capacity which might be difficult for elite athletes who already train at the limit of their endurance trainability. It seems that these effects can be best explained by changes in the triceps surae MTU mechanical properties as a stiffer tendon in conjunction with stronger muscles can enhance energy storage and release mechanisms during ground contact. Thus a heavy load strength training regimen aiming at stiffening of the tendon may be advantageous. It needs, however, been taken into account that a more compliant patella tendon may also be advantageous (Karamanidis and Arampatzis, 2005).

While weight reductions of running shoes consistently show advances in RE it cannot be concluded if minimalist shoes advance performance. Various footwear interventions appear to potentially improve RE with a lot of individual variations while some more recent footwear developments seem to show more consistent effects. As some individuals may benefit more than others from shoe these modifications it was suggested that body-inherent energy return mechanisms may be facilitated. If this is the case a comprehensive individual assessment of footwear effects including internal energy exchange mechanisms may be the only way to better understand the mechanisms used.

On the other hand, calcaneal eversion can be systematically altered by moderate inserts and leads to specific alterations in muscular activity of the leg. Individuals not following this systematic pattern are potentially working against the shoe modification leading to activity elevations in specific muscles. This finding has strong implications for overuse injuries in running which are predominantly affecting the muscle tendon complex (Nigg, 2001). The remaining subjects showed increased oxygen consumption with a medial support potentially demonstrating energy storage and release in medial structures around the ankle joint and foot. The results support the idea that footwear can be used to optimize performance based on foot movement.

In the subsequent experiment, the effect of different shoe insoles on sagittal plane kinematics, lower limb muscular activity and oxygen consumption during running on a treadmill were investigated. It was shown that ankle joint kinematics can be altered which potentially affect the energy return within the musculoskeletal system. It seems that a whole set of individual anatomical and training adaptational factors needs to be taken into account when optimizing footwear for running economy. The lengthening of the Achilles tendon during early ground contact potentially leads to a difference in energy storage but muscle activity may also change which will make it difficult to find the optimum. But the potential for energy return by tuning footwear towards intrinsic property usage may be possible and warrants further research.

The final experiment showed that insole interventions can alter gearing at the ankle joint which potentially affects energy return within the musculoskeletal system. Therefore, this alteration could have an effect on running economy which was shown by a moderate correlation.

Future research should aim at studying footwear mechanics by including the anatomical and neurophysiological mechanisms in relation to each other. This might only be possible with more invasive studies as well as using advanced modeling techniques which include sufficient anatomical detail as well as muscle mechanics.

CHAPTER 6. REFERENCE LIST

Alexander, R. M., Ker, R. F., Bennet, M. B., Bibby, S. R., Kester, R. C., (1987). The spring in the arch of the human foot. Nature 325, 147-149.

Alexander, R. M., (1991). Energy-saving mechanisms in walking and running. Journal of Experimental Biology 160, 55-69.

Anderson, T., (1996). Biomechanics and running economy. Sports Medicine 22, 76-89.

Anderson, T., Tseh, W., (1994). Running economy, anthropometric dimensions and kinematic variables. Medicine & Science in Sports & Exercise 26, S170.

Arampatzis, A., De Monte, G., Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., Bruggemann, G. P., (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. Journal of Experimental Biology 209, 3345-3357.

Aruin, A. S., Prilutskii, B. I., (1985). Relationship of the biomechanical properties of muscles to their ability to utilize elastic deformation energy. Human physiology 11, 8.

Astrand, K., Rodahl, K., Dahl, H., Stromme, S., (2007). Textbook of Work Physiology-4th: Physiological Bases of Exercise.(pp. 99-105). USA: Human Kinetics.

Astrand, P. O., (1952). Experimental studies of physical working capacity in relation to sex and age. Ejnar Munksgaard.

Aura, O., Komi, P. V., (1986). Mechanical efficiency of pure positive and pure negative work with special reference to the work intensity. International journal of sports medicine 7, 44-49.

Bailey, S. P., Pate, R. R., (1991). Feasibility of improving running economy. Sports Medicine 12, 228-236.

Bassett Jr, D. R., Giese, M. D., Nagle, F. J., Ward, A., Raab, D. M., Balke, B. R. U. N., (1985). Aerobic requirements of overground versus treadmill running. Medicine and science in sports and exercise 17, 477-481.

Bergh, U., Sjudin, B., Forsberg, A., Svedenhag, J., (1991). The relationship between body mass and oxygen uptake during running in humans. Medicine & Science in Sports & Exercise 205-211.

Biewener, A. A., (2005). Biomechanical consequences of scaling. Journal of Experimental Biology 208, 1665-1676.

Bosco, C., Montanari, G., Ribacchi, R., Giovenali, P., Latteri, F., Iachelli, G., Faina, M., Colli, R., Dal Monte, A., La Rosa, M., (1987). Relationship between the efficiency of muscular work during jumping and the energetics of running. European Journal of Applied Physiology and Occupational Physiology 56, 138-143.

Bourdin, M., Pastene, J., Germain, M., Lacour, J. R., (1993). Influence of training, sex, age and body mass on the energy cost of running. European Journal of Applied Physiology and Occupational Physiology 66, 439-444.

Bransford, D. R., Howley, E. T., (1976). Oxygen cost of running in trained and untrained men and women. Medicine and science in sports 9, 41-44.

Braunstein, B., Arampatzis, A., Eysel, P., Bruggemann, G. P., (2010). Footwear affects the gearing at the ankle and knee joints during running. Journal of biomechanics 43, 2120-2125.

Brooks, G. A., Fahey, T. D., White, T. P., (1996). Exercise physiology: Human bioenergetics and its applications. Mayfield publishing company.

Brown, C. H., (1971). Physical and physiological profiles of champion women long distance runners. Medicine & Science in Sports & Exercise 3, h.

Burkett, L. N., Kohrt, W. M., Buchbinder, R. I. C. H., (1985). Effects of shoes and foot orthotics on VO2 and selected frontal plane knee kinematics. Medicine and science in sports and exercise 17, 158-163.

Cappozzo, A., (1983). Force actions in the human trunk during running. The Journal of sports medicine and physical fitness 23, 14-22.

Carrier, D. R., Heglund, N. C., Earls, K. D., (1994). Variable gearing during locomotion in the human musculoskeletal system. Science 265, 651-653.

Catlin, M. J., Dressendorfer, R. H., (1979). Effect of shoe wight on the energy-cost of running. Williams & Wilkings, 21201-2436.

Cavagna, G. A., Kaneko, M., (1977). Mechanical work and efficiency in level walking and running. The Journal of physiology 268, 467-481.

Cavagna, G. A., Willems, P. A., Franzetti, P., Detrembleur, C., (1991). The two power limits conditioning step frequency in human running. The Journal of physiology 437, 95-108.

Cavanagh, P. R., Kram, R. O. D. G., (1985). The efficiency of human movement--a statement of the problem. Medicine & Science in Sports & Exercise 304-308.

Cavanagh, P. R., Kram, R. O. D. G., (1989). Stride length in distance running: velocity, body dimensions, and added mass effects. Medicine and science in sports and exercise 21, 467-479.

Cavanagh, P. R., Williams, K. R., (1981). The effect of stride length variation on oxygen uptake during distance running. Medicine and science in sports and exercise 14, 30-35.

Chang, Y. H., Kram, R., (1999). Metabolic cost of generating horizontal forces during human running. Journal of Applied Physiology 86, 1657-1662.

Conley, D. L., Krahenbuhl, G. S., (1979). Running economy and distance running performance of highly trained athletes. Medicine and science in sports and exercise 12, 357-360.

Costill, D. L., Thomason, H. A. R. R., Roberts, E. R. I. C., (1973). Fractional utilization of the aerobic capacity during distance running. Medicine and science in sports 248-252.

Costill, D. L., Winrow, E., (1970). A comparison of two middle-aged ultramarathon runners. Research Quarterly.American Association for Health, Physical Education and Recreation 41, 135-139.

Cureton, K. J., Sparling, P. B., (1980). Distance running performance and metabolic responses to running in men and women with excess weight experimentally equated. Med Sci Sports Exerc 12, 288-294.

Daniels, J., Oldridge, N., Nagle, F., White, B., (1977). Differences and changes in VO2 among young runners 10 to 18 years of age. Medicine and science in sports 10, 200-203.

Daniels, J. A. C. K., Oldridge, N. E. I. L., (1971). Changes in oxygen consumption of young boys during growth and running training. Medicine and science in sports 3, 161.

Daniels, J. T., (1985). A physiologist's view of running economy. Medicine and science in sports and exercise 17, 332-338.

Daniels, J. T., Yarbrough, R. A., Foster, C., (1978). Changes in VO2 max and running performance with training. European Journal of Applied Physiology and Occupational Physiology 39, 249-254.

Davies, C. T., (1980). Effects of wind assistance and resistance on the forward motion of a runner. Journal of Applied Physiology 48, 702-709.

Di Prampero, P. E., Atchou, G., Bruckner, J. C., Moia, C., (1986). The energetics of endurance running. European Journal of Applied Physiology and Occupational Physiology 55, 259-266.

Di Prampero, P. E., Capelli, C., Pagliaro, P., Antonutto, G., Girardis, M., Zamparo, P., Soule, R. G., (1993). Energetics of best performances in middle-distance running. Journal of Applied Physiology 74, 2318-2324.

Doblen, W. I. L. H., (1957). Maximal oxygen intake, body size, and total hemoglobin in normal man. Acta Physiologica Scandinavica 38, 193-199.

Ekblom, B., Astrand, P. O., Saltin, B., Stenberg, J., Wallstrum, B., (1968). Effect of training on circulatory response to exercise. Journal of Applied Physiology 24, 518-528.

Eriksson, M., Bresin, R., (2010). Improving running mechanics by use of interactive sonification. Proceedings of ISon 95-98.

Farley, C. T., McMahon, T. A., (1992). Energetics of walking and running: insights from simulated reduced-gravity experiments. Journal of Applied Physiology 73, 2709-2712.

Fletcher, J. R., Esau, S. P., MacIntosh, B. R., (2010). Changes in tendon stiffness and running economy in highly trained distance runners. European journal of applied physiology 110, 1037-1046.

Frederick, E. C., (1983). Measuring the effects of shoes and surfaces on the economy of locomotion. Biomechanical aspects of sport shoes and playing surfaces 93-106.

Frederick, E. C., Clarke, T. E., Larsen, J. L., Cooper, L. B., (1983). The effects of shoe cushioning on the oxygen demands of running. Biomechanical Measurement of Running Shoe Cushioning Properties. Biomechanical Aspects of Sport Shoes and Playing Surfaces. University of Calgary, Calgary, AB 107-114.

Gaesser, G. A., Brooks, G. A., (1975). Muscular efficiency during steady-rate exercise: effects of speed and work rate. Journal of Applied Physiology 38, 1132-1139.

Gullstrand, L., Halvorsen, K., Tinmark, F., Eriksson, M., Nilsson, J., (2009). Measurements of vertical displacement in running, a methodological comparison. Gait & posture 30, 71-75.

Hausswirth, C., Bigard, A. X., Le Chevalier, J. M., (1997). The Cosmed K4 telemetry system as an accurate device for oxygen uptake measurements during exercise. International journal of sports medicine 18, 449-453.

Hay, J. G., (1985). The biomechanics of sports techniques. Prentice Hall.

Herzog, W., Read, L. J., (1993). Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. Journal of anatomy 182, 213.

Hogberg, P., (1952). How do stride length and stride frequency influence the energy-output during running? European Journal of Applied Physiology and Occupational Physiology 14, 437-441.

Horsman, M. K., Koopman, H. F. J. M., Van der Helm, F. C. T., Pros, L. P., Veeger, H. E. J., (2007a). Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity. Clinical Biomechanics 22, 239-247.

Jones, B. H., Knapik, J. J., Daniles, W. L., Toner, M. M., (1986). The energy cost of women walking and running in shoes and bootsGêù. Ergonomics 29, 439-443.

Karamanidis, K., Arampatzis, A., (2005). Mechanical and morphological properties of different muscle tendon units in the lower extremity and running mechanics: effect of aging and physical activity. Journal of experimental biology 208, 3907-3923.

Keyrolinen H., Belli, A., Komi, P. V., (2001). Biomechanical factors affecting running economy. Aapplied Ssciences Biodynamics.

Knuttgen, H. G., (1961). Oxygen uptake and pulse rate while running with undetermined and determined stride lengths at different speeds. Acta Physiologica Scandinavica 52, 366-371.

Krahenbuhl, G. S., Morgan, D. W., Pangrazi, R. P., (1989). Longitudinal changes in distance-running performance of young males. International journal of sports medicine 10, 92-96.

Kram, R., Taylor, C. R., (1990). Energetics of running: a new perspective. Nature 265-267.

Leger, L., Mercier, D., (1984). Gross energy cost of horizontal treadmill and track running. Sports Medicine 1, 270-277.

Lichtwark, G. A., Wilson, A. M., (2007). Is Achilles tendon compliance optimised for maximum muscle efficiency during locomotion? Journal of biomechanics 40, 1768-1775.

Lichtwark, G. A., Wilson, A. M., (2008). Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running. Journal of theoretical biology 252, 662-673.

MacDougall, J. D., Roche, P. D., Bar-Or, O., Moroz, J. R., (1983). Maximal aerobic capacity of Canadian schoolchildren: prediction based on age-related oxygen cost of running. International journal of sports medicine 4, 194-198.

Maganaris, C. N., Baltzopoulos, V., Sargeant, A. J., (1998). Changes in Achilles tendon moment arm from rest to maximum isometric plantarflexion: in vivo observations in man. The Journal of physiology 510, 977-985.

Malina, R. M., Harper, A. B., Avent, H. H., Campbell, D. E., (1971). Physique of female track and field athletes. Medicine and science in sports 3, 32.

Martin, P. E., Morgan, D. W., (1992). Biomechanical considerations for economical walking and running. Medicine and science in sports and exercise 24, 467-474.

Mayhew, J. L., (1977). Oxygen cost and energy expenditure of running in trained runners. British journal of sports medicine 11, 116-121.

Mercer Jhon A., Branks Dale A., Wasserman Sarah K., Ross Chris M., (2003). Physiological cost of running while wearing spring-boots. The Journal of Strength & Conditioning Research 17, 314-318.

Moran, M. F., Greer, B. K., (2013). Influence of midsole Aactuator lugs on running economy in trained distance runners. Footwear Science 5, 91-99.

Morgan, D. W., Baldini, F. D., Martin, P. E., Kohrt, W. M., (1989a). Ten kilometer performance and predicted velocity at VO2max among well-trained male runners. Medicine and science in sports and exercise 21, 78-83.

Morgan, D. W., Craib, M. I. T. C., (1992). Physiological aspects of running economy. Medicine and science in sports and exercise 24, 456-461.

Morgan, D. W., Martin, P. E., (1986). Effects of stride length alteration on racewalking economy. Canadian journal of applied sport sciences.Journal canadien des sciences appliquees au sport 11, 211-217.

Morgan, D. W., Martin, P. E., Krahenbuhl, G. S., (1989b). Factors affecting running economy. Sports Medicine 7, 310-330.

Moritani, T., Yoshitake, Y., (1998). 1998 ISEK Congress Keynote Lecture: The use of electromyography in applied physiology. Journal of electromyography and Kinesiology 8, 363-381.

Nigg, B. M., (1986). Biomechanical aspects of running. Biomechanics of running shoes 1.

Nigg, B. M., Stefanyshyn, D., Cole, G., Stergiou, P., and Miller, J. (2003). The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. Journal of Biomechanics, 36, 569-575.

Nigg, B. M., Wakeling, J. M., (2001). Impact forces and muscle tuning: a new paradigm. Exercise and sport sciences reviews 29, 37-41.

Norman, R. W., Sharratt, M. T., Pezzack, J. C., Noble, E. G., (1976). Reexamination of the mechanical efficiency of horizontal treadmill running. Biomechanics VB. University Park Press Baltimore, pp. 87-93.

Perl, D. P., Daoud, A. I., Lieberman, D. E., (2012). Effects of footwear and strike type on running economy. Med Sci Sports Exerc 44, 1335-1343.

Petray, C. K., Krahenbuhl, G. S., (1985). Running training, instruction on running technique, and running economy in 10-year-old males. Research Quarterly for Exercise and Sport 56, 251-255.

Reinschmidt, C., Van Den Bogert, A. J., Nigg, B. M., Lundberg, A., Murphy, N., (1997). Effect of skin movement on the analysis of skeletal knee joint motion during running. Journal of biomechanics 30, 729-732.

Rowland, T. W., (1989). Oxygen uptake and endurance fitness in children: a developmental perspective. Pediatr Exerc Sci 1, 313-328.

Rowland, T. W., Green, G. M., (1988). Physiological responses to treadmill exercise in females: adult-child differences. Medicine and science in sports and exercise 20, 474-478.

Rubin, D. A., Butler, R. J., Beckman, B., Hackney, A. C., (2009). Footwear and running cardio-respiratory responses. International journal of sports medicine 30, 379-382.

Saunders, P. U., Pyne, D. B., Telford, R. D., Hawley, J. A., (2004). Factors affecting running economy in trained distance runners. Sports Medicine 34, 465-485.

Sidney, K. H., Shephard, R. J., (1977). Maximum and submaximum exercise tests in men and women in the seventh, eighth, and ninth decades of life. Journal of Applied Physiology 43, 280-287.

Snyder, K. L., Farley, C. T., (2011). Energetically optimal stride frequency in running: the effects of incline and decline. The Journal of experimental biology 214, 2089-2095.

Sparling, P. B., Cureton, K. J., (1982). Biological determinants of the sex difference in 12-min run performance. Medicine and science in sports and exercise 15, 218-223.

Storen, A., Helgerud, J., Hoff, J., (2011). Running stride peak forces inversely determine running economy in elite runners. The Journal of Strength & Conditioning Research 25, 117-123.

Tanner, J. M., (1964). The Physique of the Olympic Athlete.... Rome, 1960. George Allen and Unwin Limited.

Taylor, C. R., (1985). Force development during sustained locomotion: a determinant of gait, speed and metabolic power. Journal of Experimental Biology 115, 253-262.

Taylor, C. R., (1993). Relating mechanics and energetics during exercise. Advances in veterinary science and comparative medicine 38, 181-215.

TenBroek, T. M., Rodrigues, P., Frederick, E. C., Hamill, J., (2013). Effects of unknown footwear midsole thickness on running kinematics within the initial six minutes of running. Footwear Science 5, 27-37.

Waters, R. L., Hislop, H. J., Perry, J., Thomas, L., Campbell, J., (1983). Comparative cost of walking in young and old adults. Journal of Orthopaedic Research 1, 73-76.

Wells, C. L., Hecht, L. H., Krahenbuhl, G. S., (1981). Physical characteristics and oxygen utilization of male and female marathon runners. Research Quarterly for Exercise and Sport 52, 281-285.

Whipp, B. J., Wasserman, K., (1969). Efficiency of muscular work. Journal of Applied Physiology 26, 644-648.

Williams, K. R., Cavanagh, P. R., (1986). Biomechanical correlates with running economy in elite distance runners.

Williams, K. R., Cavanagh, P. R., Ziff, J. L., (1987). Biomechanical studies of elite female distance runners. International journal of sports medicine 8, 107-118.

Williams, K. R., (1985). The relationship between mechanical and physiological energy estimates. Medicine and science in sports and exercise 17, 317-325.

Williams, K. R., Cavanagh, P. R., (1983). A model for the calculation of mechanical power during distance running. Journal of biomechanics 16, 115-128.

Williams, K. R., Cavanagh, P. R., (1987). Relationship between distance running mechanics, running economy, and performance. Journal of Applied Physiology 63, 1236-1245.

Worobets, J., Wannop, J. W., Tomaras, E., Stefanyshyn, D., (2014). Softer and more resilient running shoe cushioning properties enhance running economy. Footwear Science 6, 147-153.

THESIS AT A GLANCE

	Primary aim	***Method***	***Main finding***
Study I	Reviews the literature on interventions to improve running economy aside from conventional endurance training methods.	24 intervention papers and four reviews which were suitable for inclusion.	Plyometric and strength training protocols were consistently beneficial to reduce the oxygen consumption per distance traveled in steady state running showing an average effect size of 3.8%. Footwear interventions showed smaller effects of 1.9% on average but still may offer considerable improvements which can potentially be applied directly.
Study II	Investigate the effect of moderate shoe inserts on calcaneal movement, muscle activity and oxygen consumption in distance running.	12 trained runners were tested with neutral and +/- 3° medial and lateral inserts. *Intervention*: Medio-lateral insoles.	Insoles potentially affect metabolic cost; however, some individuals appear to work against the anticipated effect of the insert with an increase in effort.
Study III	Influence of three difference heel positions on lower limb muscular activity and performance variable changes.	15 healthy trained male runners were tested on a treadmill submaximal pace. *Intervention:* Up (14 mm heel spring), Flat insole and Down (forefoot 5 mm higher).	Heel spring potentially changes energy exchange in the triceps surae while changes in muscle coordination may compensate for these improvements. RE is related to many factors such as running style and individual properties.
Study IV	Assess the kinematic and kinetic effects of footwear intervention by varying heel and forefoot height on ankle joint loading and Achilles tendon stretch during overground running.	11 healthy well-trained male runners. *Intervention*: Up (14 mm heel spring), Flat insole and Down (forefoot 5 mm higher).	Insole intervention altered gearing at the ankle joint and vertical force, and stretch in the Achilles tendon can be altered which potentially affects energy return within the musculoskeletal system. Therefore, this alteration could affect indirect measures of running economy

SUMMARY

The most popular activity around the world which involves the conversion of muscular forces into translocation through complex reciprocal movement patterns is running. Running economy is an important element of performance in distance running. A number of biomechanical parameters have been related to running economy and performance. Association of running mechanics with metabolic processes and economy is not well understood and very complex.

Footwear is typically a controlled variable with several design features which may influence economical running. Modifications to running shoes can be considered an obvious choice of modulating loading and with that running economy, performance and potentially overuse injuries. The muscular activations prior to touch-down are varied in response to changes in shoe construction, referred to as muscle tuning, possibly keeping the impact magnitude at an individually preferred level. The muscles around the knee and ankle joints may increase the joint stiffness, which appears to be related to better RE. Also the integration and timing of muscle activity to utilize the storage and release of elastic energy more effectively may lead to improvements in RE. It has been pointed out that substantially more elastic energy can be stored in in the muscle tendon unit of the triceps surae as compared to the energy return features found in footwear modifications.

This PhD thesis focuses on the effects of biomechanical parameters on running economy. Moreover, the effects of shoe inserts on calcaneal movement to affect energy stored in the ligaments and muscles of the foot and to modulate the energy storage and return mechanism of the triceps surae muscle group, muscle activity and running economy are investigated.

The results indicate that the energy consumption savings achieved by footwear most likely assist in improving RE by optimizing energy storage and return mechanisms within the biological system. Shoe-induced kinematic changes relate to overall metabolic cost where inserts can have the potential to regulate muscle activity and thus may affect running economy and muscle fatigue during prolonged runs. Footwear or insole interventions may alter gearing at the ankle joint and vertical force, and with that stretch in the Achilles tendon can be altered which potentially affects energy return within the musculoskeletal system. It is possible to relate gear ratio alterations to metabolic responses during a steady state treadmill run, however, the identified relationships are not direct as many factors need to be included.

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